On an innovative approach for microclimate enhancement and retrofit of historic buildings and artworks preservation by means of innovative thin envelope materials

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Abstract

Energy efficiency and environmental sustainability in building has become a key issue since the built environment is nowadays responsible for more than 30% of the total carbon emissions. While new building design and construction reached massive improvements toward net zero energy and high environmental performance standards, existing and historical buildings are still too much energy needy, with a relatively low indoor comfort conditions for both occupants and artworks preserved inside, especially within heritage buildings. Such high architectural value buildings correspond to almost one third of the Italian building stock and they typically need to be re-functionalized for hosting residential, office, or institutional uses, i.e. museums and exhibition areas. In this view, the present research aims at developing a replicable method for assessing and enhancing indoor comfort in historical buildings frequently characterized by too high relative humidity and thermal losses through the envelope. More in details, an innovative envelope material for indoor application, i.e. hygro-adsorbing plaster, has been tested in an ancient Italian castle and its effect has been assessed by means of coupled monitoring and calibrated dynamic simulation. The experimental campaign shows an increase of the Performance Index (PI) in terms of relative humidity acceptable range from 16.1% to 33.3% by applying the new thin plaster. Moreover, the results show that dedicated HVAC systems may support the action of passive strategies for preserving artworks and indoor comfort levels, but at the same time, such passive low-invasive strategies represent a mandatory first step toward energy efficiency, functional, and comfortable cultural heritage architectures.

Keywords

Cultural heritage; energy efficiency in buildings; microclimate; dehumidifying plaster; artwork preservation and indoor comfort.

1. Introduction

Over the last decade, the need for adaptation, upgrading, and energy efficiency of historic buildings has been recognized as a key-theme in the debate for the definition of a new paradigm of sustainable development. In this sense, activities aimed at the revitalization and energy-architectural upgrading of historic buildings with a high artistic and cultural value have raised great interest in the scientific community [1-3]. In particular, Italy, which represents the first country in the world for the number of UNESCO World Heritage Sites [4], is an excellent "laboratory" for the study and development of new restoration techniques able to combine conservation and energy efficiency.

Architectural renovation, energy redevelopment, and re-use of existing and historic building heritage nowadays is a widespread need in Italy where there is plenty of buildings and structures of high cultural and artistic value. In particular, the conversion of historic buildings into community structures and facilities [5,6] with public function is increasingly frequent and encouraged by local municipalities.

Reuse of historic buildings for various public functions, such as congress halls, exhibition areas and museums, is a very common practice. To this end, the microclimate within such historic buildings represents a major problem [7], especially for the preservation of art works and collections, which are often inside such structures [8]. Given the growing interest in energy efficiency and comfort of historic buildings, various attempts have been made to investigate suitable environmental conditions for both building and artworks.

Indoor environmental conditions are in fact able to significantly influence the state of conservation of the works of art. In particular, air temperature (°C), relative humidity (%), illumination level (lux), and air quality in terms of pollutants concentration (ppm) are the parameters mainly responsible for the proper preservation of cultural heritage in indoor environments [9,10]. Indeed, inadequate values of relative humidity, temperature, and illumination can lead to alteration of the physical properties of the materials of the artwork and the acceleration of the chemical degradation rate [11]. In addition, poor air quality in terms of high concentrations of pollutants can cause chemical damage to the surface of the works (corruption, oxidation) [12].

Moreover, for a proper conservation of the art works, the stability of the microclimate parameters must be guaranteed in a way that avoiding the damages caused by sudden and frequent fluctuations. In this panorama, many solutions have been proposed over the years to ensure proper environmental conditions both for the interior thermo-hygrometric comfort of the occupants and for the preservation of the artworks [13].

In general, environmental monitoring is a key activity to evaluate both quality of indoor spaces as well as the preservation of the artworks hosted in those historical building [14,15].

Correspondingly, many national and international standards and regulations have been established to recommend the methodology of collecting and analysing environmental data [16]. The standard values for indoor environmental parameters of buildings where artworks are preserved [17,18] (UNI EN 15758:2010, UNI 10969:2002, UNI 10829:1999) have been tested in field by La Gennusa et al. [19,20], through combining the two main requirements to keep in mind (i) the preservation of works and (ii) the comfort of visitors. The problem of moisture in historic buildings was addressed, for example, by Zagorskas et al. [21] by proposing and developing innovative insulation materials for the renovation of these structures.

In addition, each type of artworks needs specific microclimatic conditions according to its physical characterises. The study by Sharif and Esmaeili [22] analyse the combined effect of temperature and relative humidity on the permanence of museum objects. This study suggests to conservators to take into account the impact of indoor environmental parameters on both chemical deterioration as well as physical damage of the organic objects in order to provide the best possible combination of temperature and relative humidity for their collections. Further research on the most appropriate modalities for air-conditioning of historic buildings was carried out by Muñoz-González et al. [23], as part of the restructuring of several churches in the Mediterranean region. The study combines experimental monitoring and numerical simulation in order to identify the best retraining techniques to improve both (i) the users comfort and (ii) the artworks preservation.

2. Purpose of the work

Within the mentioned framework, this paper presents an innovative methodology coupling experimental monitoring and dynamic simulation to test the potential of passive solutions in improving the indoor thermal-hygrometric conditions within historic buildings in order to ensure both the environmental comfort of the occupants and the correct preservation of artworks exhibited inside the buildings. In particular, an innovative thin layer has been selected in order to absorb the water excess within massive walls, typically representing historic buildings. In detail, a new kind of hygro-adsorbing plaster was applied and tested in a selected area of the case study heritage building, i.e. the castle of Pieve del Vescovo (Perugia, Italy). More in details, the implemented methodology includes (i) an experimental campaign to continuously monitor the indoor microclimate of the building both before and after the application of the adsorbing plaster, (ii) the calibrated dynamic simulation of the building performance thanks to the data collected during the monitoring phase, (iii) the data analysis and the quantitative assessment of performance in order to extend the results of the experimental campaign to cultural heritage context. Then the achieved benefits are investigated in terms of the indoor microclimate of the building once the adsorbent plaster is applied to the entire structure.

3. Materials and methods

The case study is represented by the castle of Pieve del Vescovo (Fig.1), an historical building located near Perugia, central Italy (43°14’N 12°17’E). The building has three levels, a quadrangular plant with inner courtyard and four corner towers.

Fig. 1. Castle of Pieve del Vescovo**;** (a) view of the entire complex from above, (b) the main facade, south side.

The ancient castle was built in the 14th century around a pre-existing religious building dedicated to St. John the Baptist. With the permission of the municipality of Perugia, in 1396 it was fortified with massive walls and the construction of the towers. In the Renaissance period, it lost its defensive function becoming the summer residence of the bishops of Perugia and its internal finishes were therefore enriched.

The product that has been tested to evaluate the performance in terms of improving the thermo-hygrometric indoor conditions of the historic building is a natural-lime-finishing bio-plaster (Table 1) whose application is recommended for the repair of masonry affected by strong moisture. In fact, the application of the product creates a layer of strong water vapor permeability, together with high water repellence, excellent mechanical strength, and resistance to climatic agents.

Table 1. Technical specifications of the tested adsorbent plaster provided by the material producer.

Property	**Value**
Binder nature	Natural hydraulic lime NHL 3.5 Bio-sands
Maximum size of the inerts	0.6 mm
Minimum thickness (maximum size of aggregates)	2 cm (3 mm)
Bulk density of fresh mortar	1.55±0.05 kg/l
Fire resistance	Class A1
Compression strength	CS I (0.4-2.5 N/mm^2 @ 28 days)

Capillarity water absorption	W0, after 24 h 2.6 kg/m^2
Coefficient of vapor permeability	μ = 6
Thermal conductivity	0.44 W/m·K

The experimental monitoring activity consisted of the field continuous monitoring of the indoor microclimate of the Pieve del Vescovo castle's where the plaster was applied. The room chosen to test this innovative product corresponds to the base of the south-western tower of the complex. The square-shaped room has a volume about 32 m^3 while all four stone perimeter walls are in direct contact with the outside environment. Except for the access door on the east side of the room, the only opening is a small slit on the south wall. This space was continuously monitored for one week both before and after the retrofit operation. Therefore, the available experimental data allow to evaluate the thermo-hygrometric conditions of the selected space ex-ante (23 to 30 of December 2016) and ex-post (April 27 to May 4, 2017). The restauration work was carried out between March 22nd and April 19th, 2017. In details, the retrofit consisted just in the application of the above presented plaster in order to easily detect its own microclimate improvement potential. Fig. 2 shows the castle, the monitored tower as well as the monitoring station. The monitoring station used is composed of the sensors listed in Table 2, conforming to ISO 7726 [24], "Ergonomics of the thermal environment - Instruments for measuring physical quantities".

Fig. 2. (a) The monitored area of the Pieve del Vescovo castle, (b) view of the tower from the inner courtyard, (c) monitored space, (d) monitoring station installed inside the environment after retrofit action.

Table 2. Sensors that are part of the monitoring station used in the project.

Sensor	Measured parameter	Performance characteristics
Thermo-hygrometer	Air Temperature (°C) Relative humidity (%)	Resolution: 0.01°C; Uncertainty: 0.1°C Uncertainty: ±1.5%
Air and surface temperature	Temperature at the ankles (°C) Floor temperature (°C)	Resolution: 0.01°C Uncertainty: 0.15°C Resolution: 0.01°C Uncertainty: 0.15°C
Globe thermometer	Average radiant temperature (°C)	Resolution: 0.01°C; Uncertainty: 0.15°C
Hot wire anemometer	Air velocity (m/s) Turbulence (%)	Resolution: 0.01 m/s Uncertainty: 0.5÷1.5 m/s
Net radiometer	Radiant asymmetry (°C)	Uncertainty: 3%
CO sensor	CO concentration (ppm)	Resolution: 0.5 ppm; Uncertainty: 1%
VOC sensor	VOC concentration (ppm)	Resolution: 1 ppm; Uncertainty: 3%

Simultaneously to the monitoring of the area of the castle subjected to the retrofitting, other areas of the complex were continuously monitored by dedicated thermo-hygrometers to allow the calibration of the dynamic simulation model elaborated for the case study. For the monitoring of these spaces, thermo-hygrometers with an accuracy of 0.02 °C for temperature and ± 3.0% for relative humidity were used (Fig. 3).

Fig. 3. (a) Thermo-hygrometer used of continuous monitoring of four areas of the Pieve del Vescovo castle. Areas monitored: (b) classroom 1, (c) room with frescoes, (d) classroom 2, and (e) arched space.

Due to different activities taking place within the building, each area was monitored in a specific period, as summarized in Table 3.

Table 3. Monitored areas of the Pieve del Vescovo castle and the monitoring periods.

Monitored area	**Monitoring period**
Classroom 1 (Fig. 3b)	21/09-06/10/2016 28/11/2016-13/04/2017
Room with frescoes (Fig. 3c)	21/09/2016 – 14/07/2017
Classroom 2 (Fig. 3d)	21/09/2016-09/01/2017
Arched space (Fig. 3e)	21/09/2016-09/01/2017

4. Results

Given the time spent between the ex-ante monitoring week and the ex-post monitoring week of the retrofit, the analysis of the collected data is referenced to the external climatic conditions recorded in the same periods. The climate data were obtained from the weather station located at the Engineering Faculty of Perugia University, around 4 km far from the case study. Table 4 shows the results of the monitoring campaign carried out before and after the application of the adsorbing plaster within the southwest tower of the Pieve del Vescovo complex. The mean, minimum, maximum, and standard deviation of the air temperature and relative humidity recorded in the two periods are reported, both from indoor microclimate and weather monitoring stations.

Table 4. Data on the monitoring of the southwest tower (indoor) before and after the application of the adsorbing plaster, associated with the values recorded at the same time by the external weather station (outdoor).

		Air temperature (°C)		**Relative humidity (%)**	
		Indoor	**Outdoor**	**Indoor**	**Outdoor**
Pre-retrofit (23-30/12/2016)	Medium	6.7	4.8	76.7	76.6
	Maximum	8.0	13.2	100.0	99.3
	Minimum	5.3	-1.1	42.0	28.2
	Standard deviation	0.5	3.1	13.6	19.8
Post-retrofit (26/04-05/05/2017)	Medium	13.7	12.7	66.0	64.7
	Maximum	16.6	20.1	90.8	99.3
	Minimum	11.2	4.5	43.9	28.6

	Standard deviation	1.1	3.9	10.7	19.8

Table 4 shows the typical characteristic of the indoor microclimate of historic buildings. These are characterized by thick exterior walls with high thermal mass that can damp the temperature fluctuations that occur outside. Consequently, in both weeks, the maximum temperatures and minimum temperatures recorded inside are clearly attenuated with respect to the maximum and minimum outdoor temperatures. In detail, during the first week of measurements, compared to the outside temperature range recorded between -1.1 °C and 13.2 °C, inside the tower the temperature varied between a minimum of 5.3 °C and a maximum of 8.0 °C. Such behaviour is also recorded in the post-retrofit monitoring week where with an external temperature fluctuation of 15.6 °C, the one inside varies within a range of only 5.4 °C. At the same time, the calculated standard deviation inside is considerably lower (0.5 °C and 1.15 °C for the first and second monitoring weeks, respectively, against 3.1 °C and 3.9 °C for the outdoors one) where the only capacitor effect of the walls allows to maintain almost constant temperatures.

Fig.4 shows the time-trends of both indoor and outdoor records of the two main environmental parameters, i.e. air temperature (°C) and relative humidity (%), which have been collected before and after the retrofit action.

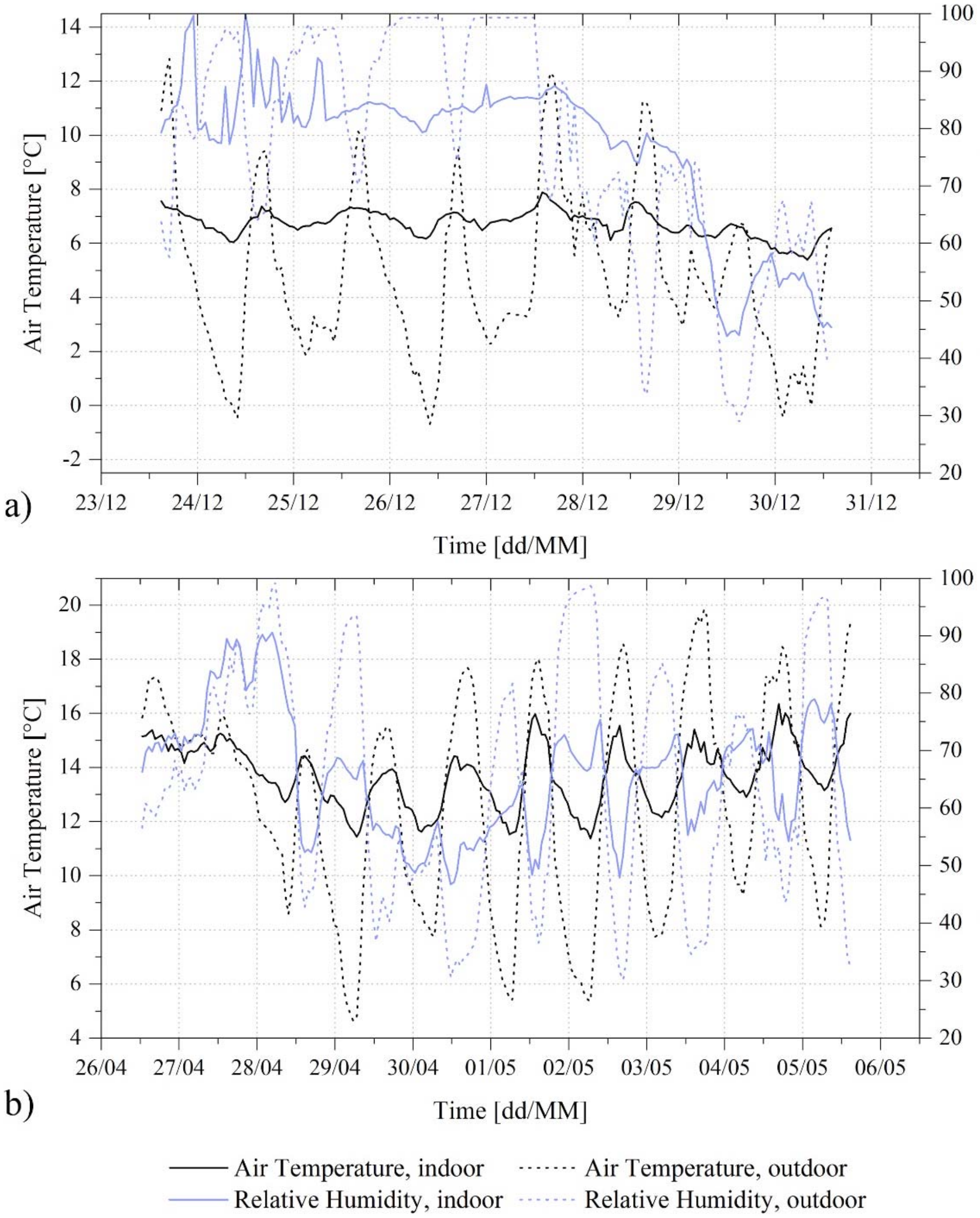

Fig. 4. Indoor and outdoor air temperature and relative humidity time-trends recorded (a) before and (b) after the application of the adsorbing plaster.

As already presented in Table 4, the graphs in Fig. show the higher sensitivity of the indoor environment to variations in humidity rather than daily temperature fluctuations. This is particularly noticeable during the first week of monitoring, characterized by colder weather conditions, when the difference between the minimum and maximum outdoor air temperature values was 14.3 °C and the indoor temperature was kept almost constant at around 6.7 °C.

During the first week of monitoring, however, the humidity of the indoor environment is not influenced by the slight fluctuations in temperature recorded inside it, but rather by the effect of external air humidity.

During the post-retrofit monitoring period, the external conditions showed more variability, and even inside, the parameters reported showed higher fluctuations than during the previous period. The correlation graphs between the internal and external microclimatic parameters in terms of temperature and relative humidity are therefore shown in Fig. 5.

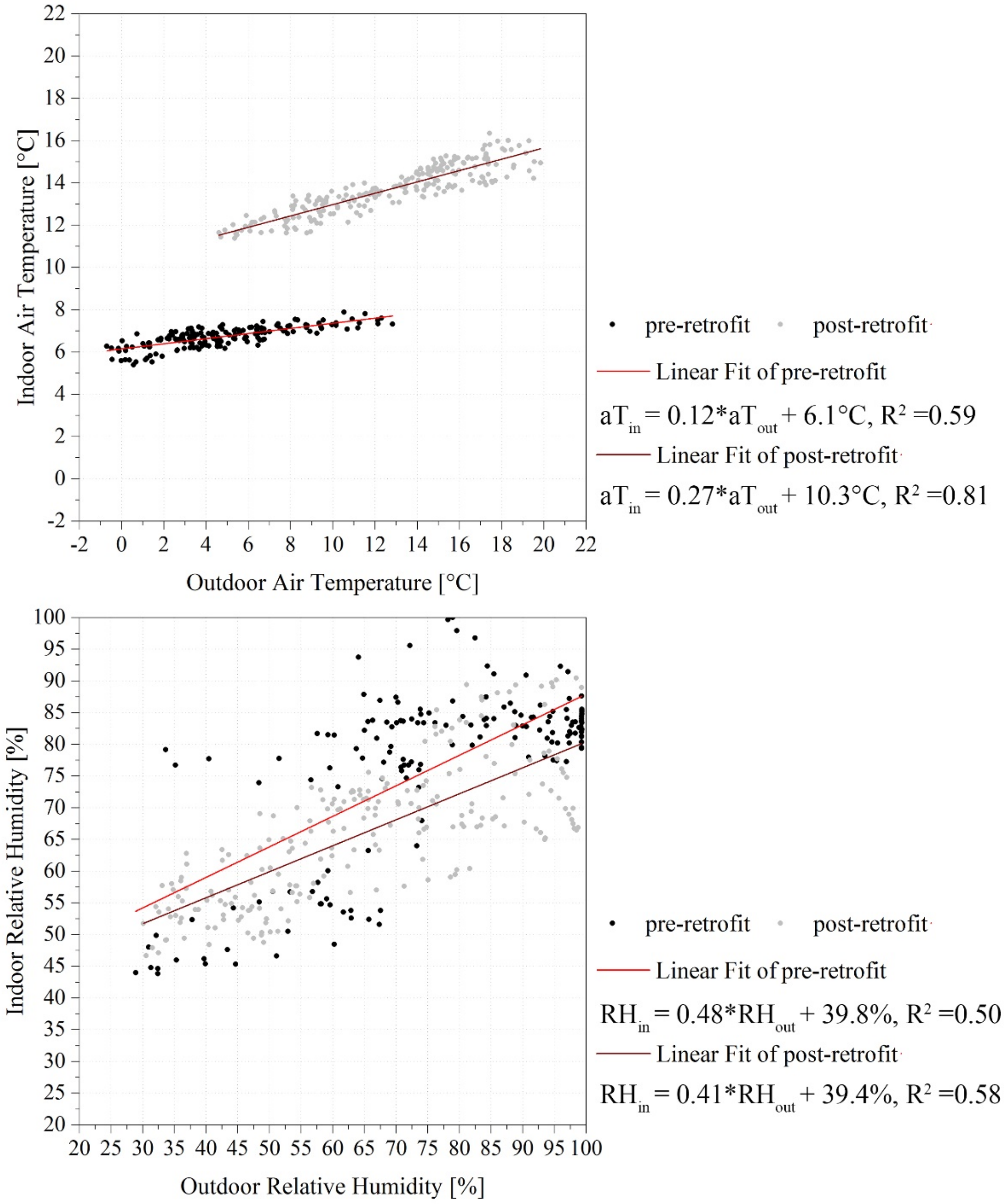

Fig. 5. Linear correlation between internal and external parameters: (a) air temperature, (b) relative humidity.

Results confirm the dampening of the internal temperature compared to the external fluctuations (correlation line slope lower than 0.3). Nevertheless, the reduced dispersion of the internal temperature values recorded results in a strong correlation between these and the external temperature (R^2=0.81). There is a weaker correlation between internal and external relative humidity, but always with a coefficient R^2 higher than 0.5. By comparing the correlation lines of the relative humidity parameter obtained in the pre- and post-retrofit period, it emerges that, due to the application of the plaster, the slope of the line decreases from 0.48 to 0.41, with the same intercept. This implies that, given the same range of relative humidity variation of the outside air, the indoor environment finished with the tested dehumidifying plaster is subject to less fluctuation of the internal humidity. It should also be highlighted that this lower variability in indoor humidity is recorded in the week characterized by wider temperature fluctuations (post-retrofit week), which disagrees with what could be expected without considering the restoration of the perimeter walls.

The results were therefore evaluated in terms of improvement of the indoor environmental parameters from the point of view of both (i) the visitors comfort and (ii) the art works preservation. The relative humidity target ranges were based on the standards, i.e. UNI EN ISO 7730 [25] for the occupants' comfort and the Italian Ministerial Decree of May 2001 [26]. With reference to the latter range, the standard suggests different limits depending on the materials being exposed in the controlled museum environment; for convenience, the most common range was chosen (45% to 60%), inappropriate only for the preservation of metals and alloys requiring moisture values of lower than 45%.

Once the reference target was identified, two indices were calculated to show the suitability of the monitored space to host artworks or to be generally open to the public [27]:

- PI (Performance Index), which represents the percentage of time in which the values of the environmental parameters fall within the target range.
- SI (Shift Index), which refers to the percentage of time when the values of the same environmental parameters do not fall within the defined target range.

Table 5 summarizes PI and SI values obtained during the environmental monitoring both before and after the retrofit operation considering occupants comfort as well as art works preservation criteria.

Table 5. PI and SI indices evaluated considering only relative humidity for the two weeks of pre- and post-retrofit monitoring. The indices were calculated both considering the target range for achieving comfort as well as that indicated for the preservation of works of art.

		Pre-retrofit (23-30/12/2016)	**Post-retrofit (26/04-04/05/2017)**
Comfort Indoor (ISO 7730)	PI	20.5 %	65.0 %
	SI	79.5 %	35.0 %
	SI <30%	0.0 %	0.00 %
	SI >70%	79.5 %	35.0 %
Art works preservation (DM 10/05/2001)	PI	16.1 %	33.3 %
	SI	83.9 %	66.7 %
	SI <45%	2.3 %	0.2 %
	SI >60%	81.6 %	66.5 %

Based on the indices obtained, it is evident that the monitored environment does not have hygrometric comfort conditions and is not suitable for the preservation of works of art. Nevertheless, an increase of the performance index (PI) occurs after the application of the adsorbing plaster. As concern the art works preservation conditions, the PI varies from 16.1% to 33.3%. Moreover, it rises up to 65.0% considering the comfort of occupants since the comfort range for humans is wider than the acceptable range for art works in terms of relative humidity.

Extending the evaluation of the monitored indoor environment by considering the air temperature, the collected data are always below 18°C as shown in Fig. 5. These results did not meet the required standard values for human comfort [25] and also for the preservation of the majority of art works typologies [26]. Therefore, in order to create a suitable environment applying this innovative plaster, it is necessary to control the environmental conditions by means of active systems.

Finally, it is necessary to point out that the dehumidifying plaster was applied exclusively on the walls of the room, but no intervention was made on the floor which is counter-ground and has a concrete finish. Fig.6 shows the recorded mean radiant temperature depending both on indoor air temperature and floor temperature.

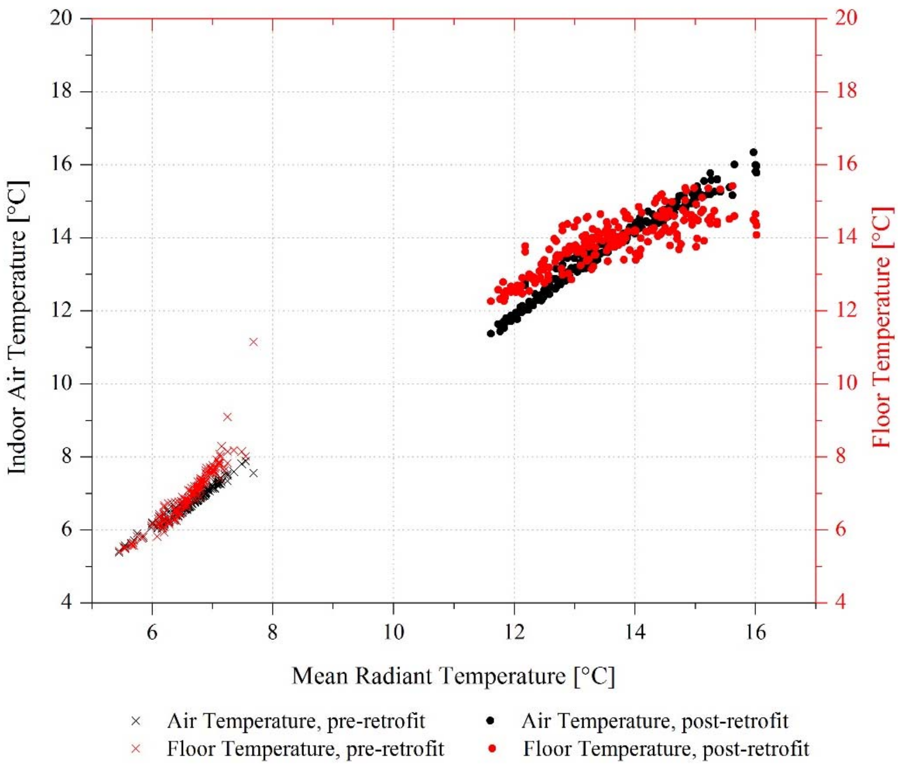

Fig. 6. Correlation of the mean radiant temperature with (i) the indoor air temperature, and with (ii) the floor temperature.

Clearly there is a strong correlation between the three parameters. The correlation between the air and the mean radiant temperature is linear, while the trend is different considering the influence of the floor temperature. In particular, the temperature of the not retrofitted surface has a stronger influence on the mean radiant temperature during the mild period, when the other surfaces enclosing the monitored space are finished with the adsorbing plaster. Therefore, it is essential to think of a retrofit strategy that covers all the elements limiting the internal space considered to obtain adequate internal conditions.

As final analysis, Fig.7 shows the concentration of Volatile Organic Compounds (VOCs) in relation to the internal temperature of the monitored environment, both before and after restauration work.

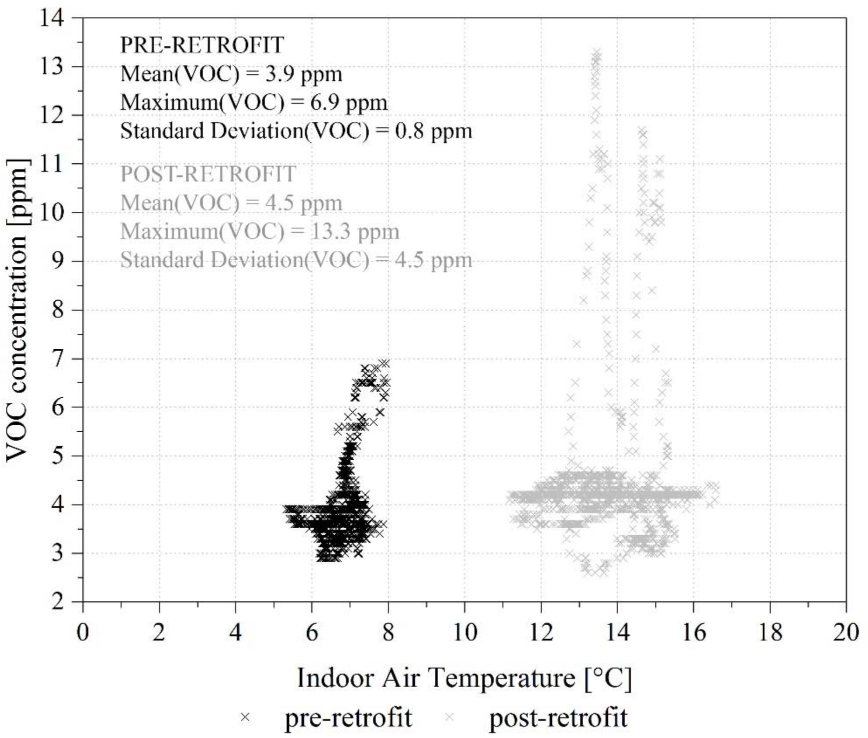

Fig.7. Correlation between the concentration of VOCs and the internal temperature. The mean, maximum, and standard deviation of the VOC concentration is also shown in the figure for the pre- and post-retrofit period.

Despite the high dispersion of recorded data, it is evident that VOC concentration increased in the environment because of the restauration. It should be noted that the monitoring was carried out one week after the end of the restauration work and that the environment has a single small outward opening to ensure a certain amount of air exchange. Concentration values, however, remain below the limits set in the literature ranging from 10 to 1000 ppm depending on the specific compound considered.

5. Dynamic simulation

As a second phase of the study, a dynamic building simulation was carried out in order to extend the results of the experimental campaign to the other thermal zones of the case study building. Accordingly, a 3D model of the castle was developed by DesignBuilder version 3.4 working with Energy Plus engine [29] to evaluate the effects on the internal microclimate resulting from the application of the adsorbing plaster within the entire castle.

The building energy model (Fig) was calibrated and validated by referring to some areas of the castle monitored by the thermo-hygrometers and listed in Table 2. Specifically, the model was calibrated according to the ASHRAE-14 standard [28] that suggests the evaluation of the Mean Bias Error (MBE) and the Root Mean Square Error (RMSE). During the calibration phase, the external wall packages and the internal thermal gains were iteratively modified to obtain a good accordance of the model which is evident from the indices shown in Table 6. Thus, the model obtained can be considered as representative of the current conditions of the building, i.e. the pre-retrofit scenario.

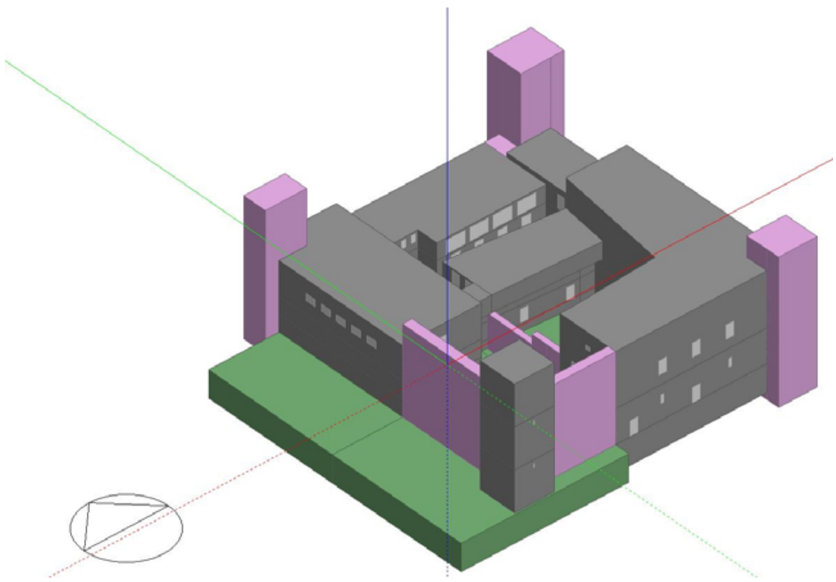

Fig.8 View of the 3D model of Pieve del Vescovo castle done with Design Builder.

Table 6. Calibration indices calculated from three different monitored areas of the building.

Monitored area	MBE	RMSE	CV(RMSE) (%)
Classroom 2	-0.13	1.45	22.4
Arched room	0.02	0.72	9.28
Room with frescoes	0.13	1.29	19.6

The application of the adsorbent plaster inside all the rooms of the castle has been simulated through the introduction of a dummy system that can guarantee the control of the internal environmental parameters. This simplification was necessary since the design model used for the simulation (DesignBuilder) is not sensitive to the specific hygrometric characteristics of the plaster and therefore fails to simulate the effect except through the introduction of systems of "equivalent" control. In particular, a fan coil unit as an active system only in the winter season was used, thus limited the indoor humidity of the environments in the most severe season.

The two models, representative of pre- and post-retrofit conditions, were simulated for a whole year using the TMY (Typical Meteorological Year) of the city of Perugia which refers to a 20-years measurement period, i.e. 1951-1970 [30]. As a part of the simulations, the presence of people within the facility was considered from 7:00 hrs to 19:00 hrs for five days a week, simulating the turnout of museum areas.

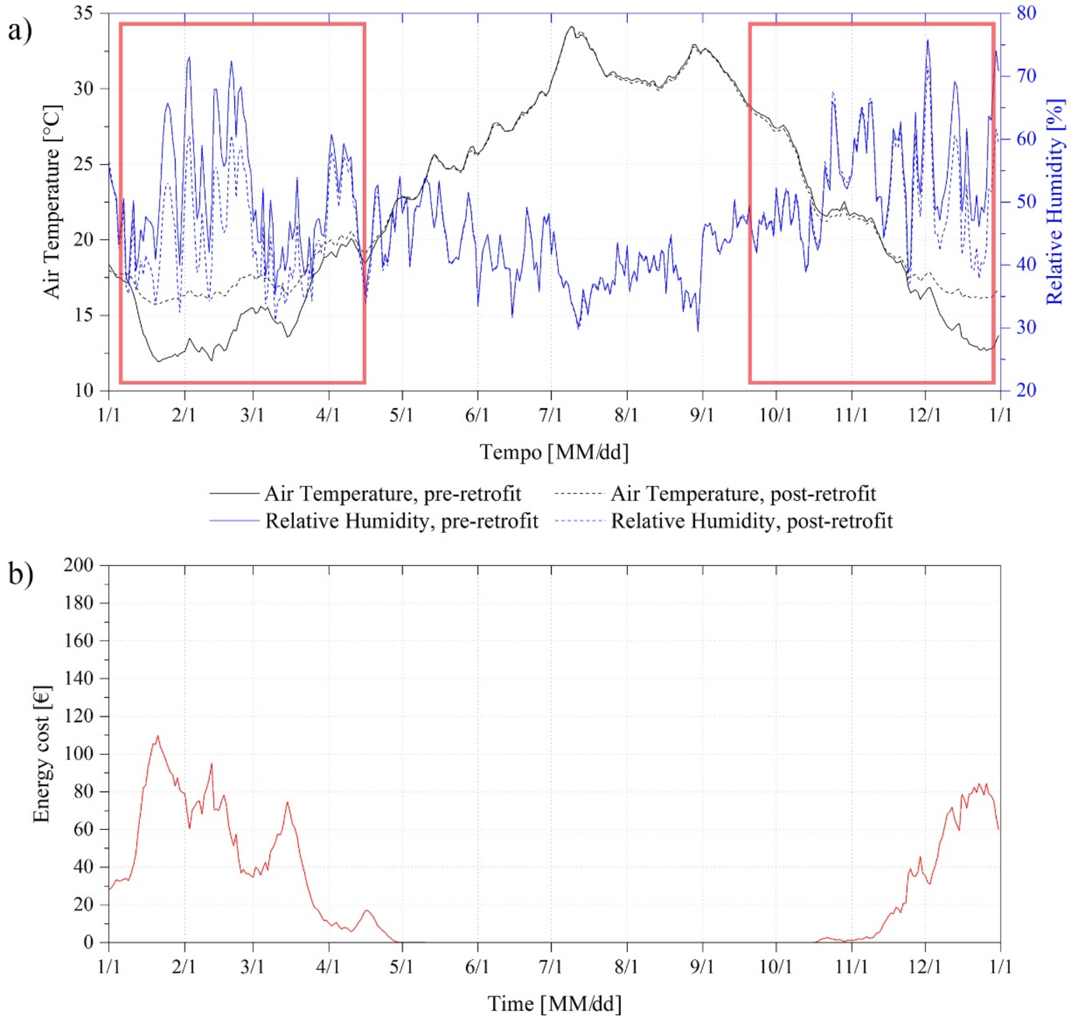

Figure 9. (a) Annual performance of simulated air temperature and relative humidity for the two different models. (b) Annual cost of the heating system, which ensures an internal moisture control close to the one due to the plaster application.

Figure 9a shows the time-trends of the indoor air temperature and relative humidity evaluated in before and after the retrofit, for the whole simulated year, while Figure 9b presents the trend, over time, of the costs related to the operation of the plant considered to simulate the presence of the plaster. In particular, the simulation shows a peak in the heating system consumption of 785 kWh during the coldest day of the year (January 21), while its total annual cost of operation is 7975.13

Euros, having taken into account the cost of energy indicated by the Statistical Office of the European Union (Eurostat) for the year 2016, i.e. 0.14 cents/kWh. This expenditure is therefore considered to be spared by the application of the equivalent passive retrofit strategy (in this case dehumidifying plaster).

Simulating the application of the plaster by means of an active system implies a wider effect concentrated in a smaller period. There is in fact a deviation of the profiles extracted from the two different models only in the winter season. The inability to modulate the control of environmental parameters over the whole year represents the limit of such simulation. However, the solution is justified by the dampening of the internal humidity fluctuations, as compared to the external outcomes of the same parameter, as shown in Fig. 10.

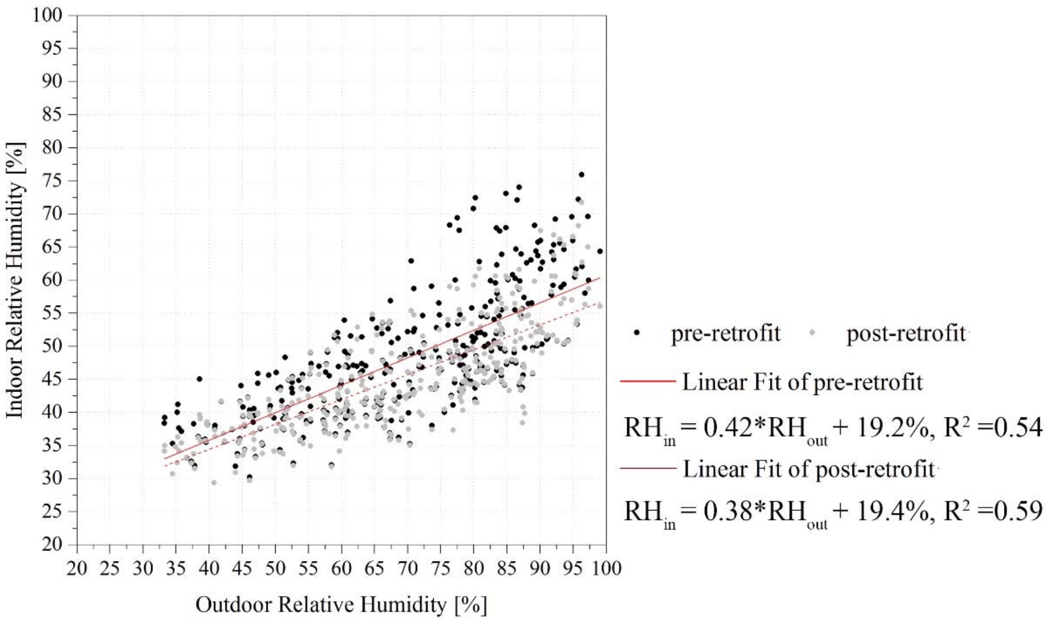

Fig. 10. Linear correlation between internal and external relative humidity before and after the retrofit in simulated conditions

Similarly to experimental results (Fig. 5b), the comparison between the correlation lines obtained from the simulation of pre- and post-retrofit models shows that, with the same intercept, the slope of the line decreases from 0.42 to 0.38 following the retrofit operation. For the same variation of the external parameter, the indoor humidity variation is lower.

Finally, an assessment of possible benefits can be obtained in terms of comfort of occupants and maintenance of the optimal microclimate conditions for the preservation of artworks. As in the previous section, PI and SI indices were obtained, considering the relative humidity ranges suggested by the standards (Table 7).

Table 7. PI and SI indices obtained from dynamic model simulation in pre- and post-retrofit conditions. The indices were calculated both considering the target range for achieving comfort as well as that indicated for the preservation of works of art.

		Pre-retrofit	Post-retrofit
Comfort Indoor (ISO 7730)	PI	97.8 %	99.2 %
	SI	2.2 %	0.8 %
	SI $_{<30\%}$	0.3 %	0.6 %
	SI $_{>70\%}$	1.9 %	0.2 %
Conservations works (DM 10/05/2001)	PI	44.7 %	41.4 %
	SI	55.3 %	58.6 %
	SI $_{<45\%}$	43.0 %	53.2 %
	SI $_{>60\%}$	12.3 %	5.4 %

The percentage of time for which the recorded humidity fits the target range proposed by DM 10.05.2001 [26] for the proper preservation of works of art is reduced in the post-retrofit simulated scenario with respect to the pre-retrofit one. In particular, the air is excessively dry when the heating system is active. This result points out another limit of using an active system as an alternative for simulating the effect of passive mitigation strategy. The effect of the active system is more concentrated in time and intensity than expected by plaster application. Therefore, better conditions should be achieved by a real application. Nevertheless, the simulation results are justified considering the whole year run since it shows the decoupling of the internal parameters from the exterior ones (Fig.10).

6. Conclusions

This paper presents the results of microclimatic monitoring and thermal-energy analysis of the Pieve del Vescovo castle, an historical building located in central Italy. The aim of the study was to define a replicable methodology for selecting and designing proper materials for the retrofit of historic buildings and improving the indoor microclimate. The internal thermal-hygrometric conditions were evaluated by considering both the comfort of occupants and the proper preservation of the artworks inside the building.

The activity started with the continuous monitoring of key environmental parameters within the strategic castle areas. In this phase, attention was paid to the monitoring of the south-western tower of the complex selected to test the application of an innovative adsorbent plaster for indoor envelope application. The mentioned area was then monitored both before and after the application of the finishing material.

At a later stage, the dynamic simulation model of the Pieve del Vescovo castle was elaborated to evaluate the impact of the plaster, which was experimentally tested in one single room, applied on the whole complex. The results of the simulation were post-processed in terms of energy saving and indoor microclimate enhancement.

The experimental analyses demonstrated a dampening of the relative internal moisture fluctuations attributable to the presence of adsorbent plaster. The PI increases from 16.1% to 33.3% just considering the optimal relative humidity range for artworks preservation and it rises up to 65.0% taking into account occupants comfort. Despite this, the values were still far from the range of comfort offered by the regulations, especially in terms of air temperature values. Therefore, the implementation of both passive and active strategies is suggested to convert historic buildings into museum spaces, always respecting the constraints that the building is subjected to.

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